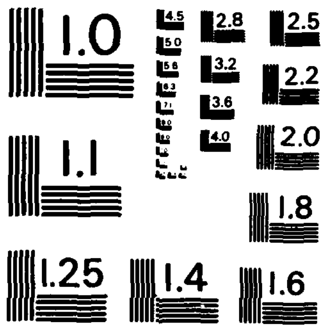
AD-A160 769 REVIEW OF ULTRASONIC VELOCITY METHODS OF DETERMINING RESIDUAL STRESS(U) AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA) S J RUMBLE ET AL. MAY 85 ARL/STRUC-TM-416 1/1

UNCLASSIFIED F/G 20/11 NL

END



UNCLASSIFIED

(12)

ARL-STRUC-TM-416

AR-004-030

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AD-A160 769

Structures Technical Memorandum 416

REVIEW OF ULTRASONIC VELOCITY METHODS OF DETERMINING RESIDUAL STRESS

by

S.J. RUMBLE and J.G. SPARROW

Approved for Public Release

85 10 31 077

MAY 1985

AR-004-030

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORIES

Structures Technical Memorandum 416

REVIEW OF ULTRASONIC VELOCITY METHODS OF DETERMINING RESIDUAL STRESS

by

S.J. RUMBLE and J.G. SPARROW

SUMMARY

This paper summarizes the techniques used to determine residual stresses. It notes that ~~whilst~~ while velocity methods have not been refined to the stage of practical use, they show considerable promise. The theoretical basis, and the experimental techniques of the ultrasonic methods are reviewed with emphasis on the separation of the competing effects of texture and stress on ultrasonic velocity. Keyword: Australia

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia.

CONTENTS

Page No.

1. INTRODUCTION 1

2. METHODS OF MEASURING RESIDUAL STRESS 1

3. ULTRASONIC METHODS 2

4. TEXTURE 4

5. TECHNIQUES OF MEASUREMENT OF ULTRASONIC VELOCITIES 5

6. EXPERIMENTAL DIFFICULTIES 7

7. DISCUSSION 9

REFERENCES

DISTRIBUTION

DOCUMENT CONTROL DATA

1. INTRODUCTION

Residual stress is the stress remaining in a body when all external forces have been removed. Residual stresses can occur as a result of fabrication, assembly, load history, heat treatment or welding. They may be compressive or tensile, and often contribute to the occurrence of component failure. The contribution of these stresses to premature structural failure has long been recognised. However their measurement has usually been difficult and in many cases not possible. Recognition of the benefits of knowing the value of residual stresses has led to recent efforts to improve the capability of known methods of measuring them and to the development of new techniques.

The residual stresses in a body can be divided into two classes depending on the extent of the stress. In typical engineering materials, residual microstresses extend over a few grains, whereas residual macrostresses occur on a scale of millimetres or greater. It is the residual macrostresses which are most amenable to the practical measurement methods discussed in this paper.

2. METHODS OF MEASURING RESIDUAL STRESS

The earliest method of determining residual stress was based on the hole drilling technique wherein measurements are made of the relaxation strains resulting from the drilling of a small hole in the centre of a strain gauge rosette[1]. While this method is semi-destructive, it is both simple and inexpensive to apply and can be used both in the laboratory and as a field measurement[2]. The method is presently limited to stress fields uniform with depth, having a stress less than approximately one third of the yield strength of the material. While the equipment needed is relatively inexpensive, the method requires skilled technicians to ensure that the hole location and diameter are within close tolerances[3].

The most widely used non-destructive method of measuring residual stress is that of X-ray diffraction[4].(XRD). This technique is based on the determination of the interatomic spacing of lattice planes in the specimen surface layer (25 μ). The procedure has been well developed

over the past twenty years and remains the only practical method in many situations[5]. Its most significant limitation may be the fact that the technique is only surface sensitive, while in the presence of strong texture and large grain size, for example in some aluminium alloys, the XRD results may be difficult to interpret. Energy dispersive X-ray spectrometry (EDXRS) using a range of high energy X-rays capable of penetrating considerable depths into steel offers the prospect of overcoming the surface limitation of XRD. The EDXRS method still requires considerable development before its full potential is reached[6].

Ultrasound methods have not yet been refined to a stage where they may be put to practical use for the measurement of residual stress. However they offer such promise, particularly for three-dimensional stress fields, that intense research effort continues to be devoted to their development[7].

Other potential methods of measuring residual stress have been suggested (Barkhausen[8,9]; nuclear hyperfine[10]; neutron diffraction[11]) but only neutron diffraction appears to offer potential for other than very limited application. A number of recent reviews of non-destructive methods of residual stress measurement have been published[7,10,12-14].

3. ULTRASONIC METHODS

The anharmonicity (higher order strain terms in the strain energy expression) of a material provides the physical basis for the measurement of stress/strain by ultrasound[15]. Most frequently, use is made of the approximately linear change in ultrasound velocity with absolute stress, and it is the application of this principle which will be discussed subsequently. Based on Murnaghan's[16] theory of finite deformations, Hughes and Kelly[17] formulated the following expressions for the velocities of elastic waves in an isotropic material under uniaxial stress:

$$\rho_o V_L^2 = \lambda + 2\mu - \frac{T}{3K_o}\left[2l + \lambda + \frac{(\lambda+\mu)}{\mu}(4m + 4\lambda + 10\mu) \right] \quad (1)$$

$$\rho_o V_T^2 = \mu - \frac{T}{3K_o}\left[m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu\right] \quad (2)$$

For propagation perpendicular to the direction of stress

$$\rho_o V_L^2 = \lambda + 2\mu - \frac{T}{3K_o}\left[2l - \frac{2\lambda}{\mu}(m + \lambda + 2\mu)\right] \quad (3)$$

$$\rho_o V_{T1}^2 = \mu - \frac{T}{3K_o}\left[m + \frac{\lambda n}{4\mu} + \lambda + 2\mu\right] \quad (4)$$

$$\rho_o V_{T2}^2 = \mu - \frac{T}{3K_o}\left[m - \frac{(\lambda+\mu)n}{2\mu} - 2\lambda\right] \quad (5)$$

where ρ_o is the material density at zero strain, T is the applied stress, positive being compressive and the L and T refer to longitudinal and transverse waves. The subscripts T1 and T2 refer to shear wave polarisation parallel and perpendicular to the direction of stress respectively. λ and μ are Lamé constants, while l, m, and n are *Murnaghan constants.* $K_o = \lambda + \frac{2}{3}\mu$ is the bulk modulus for the isotropic material in the unstrained state.

From the above equations, in the first approximation, linear relationships can be shown between both shear and longitudinal wave velocities and uniaxial stress. In addition for shear waves

$$\frac{V_{T2} - V_{T1}}{V_{T0}} = \frac{T}{8\mu^2}(4\mu + n) \quad (6)$$

where $V_{T_o} = \left(\frac{\mu}{\rho_o}\right)^{1/2}$ is the transverse wave velocity in the unstressed isotropic material.

Equation (6) is the basis for the advantage of the acoustic birefringence technique compared to the method based on measurement of longitudinal wave velocity. Whereas the latter requires very precise measurement of absolute velocities taking account of changes in length and temperature, acoustic birefringence is largely self-calibrating since only a differential velocity need be measured.

The above equations indicate that if the ultrasonic velocities in a uniaxially stressed, but otherwise isotropic material, could be determined, then a map of the relative stresses (residual and applied stresses) in the material could be obtained. If the velocity at zero stress was known or could be determined then the absolute stresses could be calculated, which in the absence of any applied stresses would be the residual stresses. However most metals, as a consequence of their thermal history and mechanical working during fabrication, contain some degree of "texture". The effect of texture on ultrasonic velocities is often the same as, or an order of magnitude larger than, that contributed by stress (40). This variation of velocity with texture or the presence of any residual stress does not affect the determinations of applied stresses, as the texture or residual stress altered velocity is still linearly related to any applied stress. This has enabled measurements of applied stress, using either longitudinal or shear waves, to become a practical and relatively straightforward procedure. However, to determine the residual stress at a given location, it is necessary to separate the contributions of texture and stress to the ultrasonic velocity.

4. TEXTURE

At the present time there are only three approaches which offer some prospect for this separation. In 1966 Mahadevan[41] reported that for a steel specimen there is a linear relationship between the shear wave birefringence due to texture and frequency (between 2-5 MHz), and that the effect of stress is the same at each frequency. This offers the possibility of separating the two components of the observed birefringence. In 1968 Reynolds[42] showed that, while each of the two shear wave and the longitudinal wave velocities is strongly affected by material texture, the sum of the squares of the three velocities is constant, independent of orientation of the crystallite axis and grain alignment. Furthermore from equations (3), (4) and (5) it can be shown that[40]

$$\rho_o \sum_{n=1}^{3} V_n^2 = (\lambda + 4\mu) - \frac{PT}{3k_o} \qquad (7)$$

where

$$P = 2\ell + 2m + 2\mu - 5\lambda - \frac{1}{4\mu}(\lambda n + 8\lambda m + 8\lambda^2 + 2\mu n) \qquad (8)$$

indicating that the velocity combination is linearly dependent on stress. Other texture independent formulae have been derived[43] although none of them is as straightforward as equation (7).

An alternative approach to the determination of stress from the velocity of ultrasonic waves has been developed by Salama[38,44] and by Chern et al[39]. They have reported that the relative change in the temperature dependence of longitudinal velocity is a linear function of applied stress, the slope of this relationship being the same for all specimens of the same material tested. In addition they reported that the same relationship applies for a number of different aluminium alloys indicating that it is insensitive to both composition and texture.

5. TECHNIQUES OF MEASUREMENT OF ULTRASONIC VELOCITIES

The most commonly used methods of measuring ultrasonic transit times are based on the sing-around, pulse-echo overlap and superposition techniques. The sing-around method involves the successive retriggering of the emitting transducer by selected echoes received by a further receiving transducer on the opposite side of the specimen; or by the reflected echo returning to the emitting transducer. The frequency of retriggering is a measure of the transit time of the ultrasonic wave across a single or double path through the specimen. This repetition frequency can be measured to a precision of a few parts in 10^7 [18], probably in excess of that required in view of other sources of uncertainty (eg. $\pm$ .001^{o}C results in $\pm$ 2 in 10^7 for $\Delta V/V$ for most materials[19]).

In the pulse superposition method, the transducer is triggered by an oscillator whose frequency is manually adjusted until its reciprocal coincides with the round-trip transit time (or a multiple) of the ultrasonic wave in the specimen. Adjustment of the oscillator frequency is carried out to achieve overlap of an echo with a later echo in the same pulse train. Summation of coincident pulses occurs at the transducer and is observed on a CRO screen [20] or more recently as calculated by a computer[21]; in this latter system, a detection sensitivity of 1 part in 10^8 is claimed. In both the sing-around and pulse superposition techniques, a number of pulse trains are in the material at any one time. This occurs because the emitting transducer is retriggered before the ultrasonic pulse from the previous triggering has completely decayed.

The pulse echo overlap method is generically related to the superposition method except that the transducer excitation rate is low enough that all echoes decay before the transducer is retriggered. The echo overlap is achieved by adjusting the sweep frequency of a CRO to be equal to the reciprocal of the travel time in the specimen, and enhancing the CRO intensity during passage of the pair of echoes under examination. In this case overlap occurs optically in the CRO rather than in the transducer as with the superposition method. The transducer triggering frequency is obtained by division of the reciprocal of the echo travel time by a factor of 100 - 1000; reduction of this factor to 1 would make this technique equivalent to the superposition method. The pulse echo overlap technique has been developed and extensively used by Papadakis[22]. A comparison of a number of methods of measuring ultrasonic velocity is given in a review paper by that author[19].

Adaptation of the above methods have included the use of an ultrasonic delay line to achieve overlap between successive pulses[23]; the interference between echoes from passage of an ultrasonic puse through two specimens, one under stress[24]; and the use of separate transducers each side of the specimen to generate two principal shear waves with a variable electrical delay between them adjusted to achieve echo cancellation[25].

The use of shear rather than longitudinal ultrasonic waves introduces the possibility of another method of velocity measurement. In a stressed

or slightly anisotropic material, a shear wave will in general split into two polarised components with different velocities. Rotation of the shear wave transducer into an alignment with respect to the principal stress directions (for an isotropic material) or to the rolling direction for a textured specimen enables examination of a single polarised component; the above methods of velocity measurement can then be applied. For any other transducer orientation, the presence of the two polarised components generally requires another technique of measurement unless the differential velocity is large enough to provide temporal separation of the components[26].

Individual meausrement of the velocities of the two perpendicular components appears to be the most popular approach to the use of shear wave birefringence[27-32]. However some authors have exploited pulse spectroscopy whereby the two shear waves are allowed to interfere at the transducer and the echo of minimum amplitude determined[33-36]. Whereas in the past some form of frequency measurement has usually been adopted to achieve the necessary transit time precision, the advent of high frequency A/D converters has led to the use of Fourier transform computer methods of calculating phase[26,37].

6. EXPERIMENTAL DIFFICULTIES

Difficulties associated with the determination of residual stress using ultrasound are exacerbated by the relatively small stress induced velocity changes, of the order of 10^{-5}/MPa. Timing of the precision required (say ± 1 nsec) can now be readily achieved. However for longitudinal waves there is also a need for accurate path length (even an error of 1 part is 10^4 in the length results in a stress uncertainty of 10 MPa) and temperature measurements; changes in temperature must also be minimised to reduce its effect on path length (since the coefficient of linear expansion of aluminium is approximately $2 \times 10^{-5}/^{o}C$) and more directly because of the high temperature coefficient of sound velocity ($\sim 1.5 \times 10^{-4}/^{o}C$). One of the advantages of measuring acoustic birefringence is that the above problems are largely eliminated since the differential measure $\Delta V_s/V_s$ incorporates self-cancellation of the effects of changes of length and temperature.

On the other hand longitudinal waves may be launched into a metallic specimen through a simple fluid coupling, water[45] or ethylene glycol[46] being commonly used. Shear wave coupling requires the medium of a viscoelastic fuild although cementing the transducer to the surface would be preferred. Some authors have successfully employed dry coupling using interface pressure to achieve a reasonable level of shear energy transmission[28]. The problem of shear wave coupling is accentuated for techniques which require measurements of the polarised components at two perpendicular orientations of the transducer. The difficulties of maintaining constant bond conditions while rotating a narrow bandwidth transducer have been highlighted by a number of workers[31,34], although others have either reported no problems or perhaps failed to verify their absence. Rudd[12] considers the area of transducer/specimen coupling to be one of the four major problem areas limiting the practical application of ultrasonic shear wave measurements of residual stress. Since the bond properties may also be frequency dependent, additional complications are introduced when measurements are carried out at a number of frequencies either with separate transducers or with a single broadband transducer. Some workers have overcome the variability of bond properties by keeping the transducer fixed during measurements, while others have overcome the bonding problem by changing from piezoelectric transducers to electromagnetic acoustic transducers (EMAT's)[32,47-49]. The pulse spectroscopy approach does not require rotation of the transducer, nor does the method introduced by Arora and James. However in this latter experiment, the high degree of specimen texture and therefore birefringence was advantageous as the well separated polarised components were amenable to Fourier transform processing[26].

Simple application of both the sing-around and the pulse superposition methods tend to measure an ill-defined group velocity in a dispersive or attenuative medium. Since the group velocity relates to the required phase velocity by the expression

$$C_g = C_p - \lambda \frac{dC_p}{d\lambda} \qquad (9)$$

this would result in an error in the calculated stress values unless a correction is made. The pulse echo overlap method is capable of measuring group velocity, while the choice of the proper cyclic overlap permits accurate measurement of phase velocity[50]. A theoretical study of the potential errors in phase velocity measurements by pulse methods in dispersive media has been made by Edwards[51], while Papadakis[52], and Sachse and Pao[53] have discussed procedures aimed at ensuring that these sources of uncertainty are minimised. A practical algorithm for the correction of spurious 2π errors arising in a Fourier transform technique for determining phase using short duration pulses has been outlined by Allen and Cooper[37].

The effect of diffraction in increasing the measured wave velocity compared to the plane wave value has long been recognised[54]. Theoretical analyses confirmed by experimental measurements indicate that diffraction errors may be reduced by increasing the effective path length over which the waves are transmitted[50,55,56]. The Harwell group[47] have given a clear illustration of the asymptotic nature of the time delay between successive pulses indicating the need to concentrate on the interval between higher order pulses if accurate results are to be obtained. Unfortunately this benefit may well be offset by the larger error which may then be expected as a consequence of the interference from mode converted pulses.

7. DISCUSSION

The early development of the theoretical basis of acoustoelasticity is credited to Hughes and Kelly[17]. The derived equations relating the velocity of elastic waves in terms of finite strains and the second and third order elastic constants, from which they found the stress dependent relationships by assuming the simple stress-strain formulae. The need to resolve the dependency of ultrasonic velocity on stress and on strain has been highlighted by McDonald[57] whose mathematical model suggested a dependence on both parameters. In the use of acoustoelasticity for the measurement of residual stress resulting from plastic deformation, the assumption has generally been made that the velocity is a function only of

assumption has generally been made that the velocity is a function only of stress. For a non-work-hardening material, this is equivalent to specifying that the ultrasonic velocity is constant during yielding and that the change in velocity during unloading follows the same relationship as during loading[58]. This assumption has been tested by Okada[35] who concluded that for his 1100 aluminium specimen the ultrasonic birefringence was directly related to stress and not to strain. Johnson[46], using longitudinal waves, reached a similar conclusion for the alloy 2024-T351, but for two other aluminium alloys an additional strain dependence was also apparent. Further work, both theoretical[59] and experimental, on the effect of elastic-plastic deformation on ultrasonic wave velocity is clearly desirable.

Much of the work already discussed has been based on one dimensional velocity measurements on uniaxial stress fields. However the ultimate aim of ultrasonic stress measurements must be the development of 3D methods. The Stanford group has already shown their capability of using longitudinal velocity measurements to map the 2D stress fields in a number of situations[45,60-63]; and by using a focussed acoustic beam and a differential phase contrast technique they have achieved stress field measurements in three dimensions[64]. Extension of their work to mapping with shear waves is proceeding. A number of other groups have also been active in these areas[31] or in exploring ultrasonic tomography as a tool for 3D stress measurements[65-67]. The complementary nature of longitudinal and shear waves for 2D mapping is noted.[31]. The former give information about the sum of the principal stresses for the plane stress state, while shear waves can provide detail of the differences in the principal stresses.

The ultrasonic measurement of applied stress is currently both feasible and practical. Extension of the technique to include residual stress measurement still must await a convincing algorithm for separating the competing effects of texture and stress. Although its implementation is still many years away, the prospect of 3D stress measurement by ultrasonic means continues to stimulate considerable research effort.

REFERENCES

1. J. Mathar, *Determination of initial stresses by measuring the* deformation around drilled holes. Trans. ASME 56(4), 1934, pp. 249-254.

2. --- Standard method for determining residual stresses by the hole drilling strain-gauge method. ASTM E837-81.

3. N.J. Rendler and I. Vigness, Hole-drilling strain gauge method of measuring residual stresses. Proc. Soc. Exp. Stress Analysis 23(2), 1966, pp. 577-586.

4. C.O. Rudd, X-ray analysis and advances in portable field instrumentation. Journal of Metals 31(6), June 1979, pp. 10-15.

5. G. Maeder, J.L. Lebrun and J.M. Spravel, Present possibility for the X-ray diffraction method of stress measurement. NDT Int. 14, Oct. 1981, pp. 235-247.

6. C.J. Bechtoldt, R.L. Placious, W.J. Bottinger and M. Kuriyama,. Adv. in X-ray analysis 25, 1981, pp. 229-

7. C.O. Rudd, A review of nondestructive methods for residual stress measurement. Journal of Metals 33, July 1981, pp. 35-40.

8. O. Sundstrom and K. Torronen, The use of Barkhausen noise analysis in nondestructive testing. Mat. Eval. 37(3), Feb. 1979, pp. 51-56.

9. C.G. Gardner, G.P. Matzkanin and D.L. Davidson, The influence of mechanical stress on magnetization processes and Barkhausen jumps in ferromagnetic materials. Int. Journ. Nondest. Test. 3(2), Sept. 1971, pp. 131-169.

10. M.R. James and O. Buck, Quantitative nondestructive measurements of residual stresses. CRC Crit. Reviews in Solid State and Materials Sciences 9, 1980, pp. 61-105.

11. A. Allen, C. Andreani, M.T. Hutchings and C.G. Windsor, Measurement of internal stress within bulk materials using neutron diffraction. NDT Int. 14, Oct. 1981, pp. 249-254.

12. C.O. Rudd, A review of selected non-destructive methods for residual stress measurement. NDT Int. 15, Feb. 1982, pp. 15-23.

13. T.R. Finlayson, Residual stress analysis: a review. Metals Forum 6(1), 1983, pp. 4-10.

14. R.A. Coyle, The measurement of residual stress. Non-Destructive Testing 21(1), 1984, pp. 6-9.

15. R.E. Green, Jr., Ultrasonic investigation of mechanical properties. Published as Treatise on Materials Science and Technology. Vol. 3, Academic Press: New York, 1973.

16. F.D. Murnaghan, Finite deformation of an elastic solid. John Wiley and Sons: New York, 1951.

17. D.S. Hughes and J.L. Kelly, Second-order elastic deformation of solids. Phys. Rev. 92(5), 1953, pp. 1145-1149.

18. R.L. Forgacs, Improvements in the sing-around technique for ultrasonic velocity measurements. J. Acoust. Soc. Amer. 32(12), Dec. 1960, pp. 1697-1698.

19. E.P. Papadakis, The measurement of small changes in ultrasonic velocity and attentuation. CRC Critical Reviews in Solid State Sciences 3, August 1973, pp. 373-415.

20. H.J. McSkimin, Pulse superposition method for measuring ultrasonic wave velocities in solids. J. Acoust. Soc. Amer. 33, 1961, pp. 12-16.

21. Y.K. Yogurtcu, E.F. Lambson, A.J. Miller and G.A. Saunders, An apparatus for high precision measurements of ultrasonic wave velocity. Ultrasonics 18, July 1980, pp. 155-159.

22. E.P. Papadakis, New compact instrument for pulse-echo-overlap measurements of ultrasonic wave transit times. Rev. Sci. Inst. 47(7), July 1976, pp. 806-813.

23. R.H. Bergman and R.A. Shahbender, Effect of statically applied stresses on the velocity of propagation of ultrasonic waves. J. App. Phys,. 29, 1958, pp. 1736-1738.

24. F.R. Rollins, Study of methods for non-destructive measurement of residual stress. WADC Tech. Report 59-561, 1959.

25. R.T. Smith, Stress induced anisotropy in solids - the acoustoelastic effect. Ultrasonics 1, 1963, pp. 135-147.

26. A. Arora and M.R. James, Ultrasonic measurement of residual stress in textured materials. J. Test and Eval. 10(5), Sept. 1982, pp. 212-216.

27. H. Fukuoka, H. Toda and T. Yamane, Acoustoelastic stress analysis of residual stress in a patch-welded disk. Exp. Mech. 18, 1978, pp. 277-280.

28. D.I. Crecraft, The measurement of applied and residual stresses in metals using ultrasonic waves. J. Sound Vib. 5(1), 1967, pp. 173-192.

29. N.N. Hsu, Acoustical birefringence and the use of ultrasonic waves for experimental stress analysis. Exp. Mech. 14(5), 1974, pp. 169-174.

30. E. Schneider and K. Goebbels, Determination of residual stress by time of flight measurements with linear-polarised shear waves. Ultrasonics Symp. IEEE 1981, pp. 956-959.

31. A.V. Clark, R.B. Mignogna and R.J. Sanford, Acousto-elastic measurement of stress and stress intensity factors around ~ack tips. Ultrasonics 21, March 1983, pp. 57-64.

32. R.B. King and C.M. Fortunko, Determination of in-plane residual stress states in plates using horizontally polarised shear waves. J. Appl. Phys. 54(6), 1983, pp. 3027-3035.

33. F. Bach and V. Askegaard, General stress-velocity expressions in acoustoelasticity. Exp. Mech. 19, 1979, pp. 69-75.

34. J. Blinka and W. Sachse, Application of ultrasonic-pulse-spectroscopy measurements to experimental stress analysis. Exp. Mech. 16(2), 1976, pp. 448-453.

35. K. Okada, On the hysteresis property in acoustoelastic effect. Jap. Journ. App. Phys. 21, 1982, Supp. 21-3, pp. 126-128.

36. E.P. Papadakis, Ultrasonic spectroscopy applied to double refraction in worked metals. J. Acoust. Soc. Amer. 55(4), April 1974, pp. 783-784.

37. D.R. Allen and W.H.B. Cooper, A Fourier transform technique that measures phase delays between ultrasonic impulses with sufficient accuracy to determine residual stresses in metal. NDT Int. 16(4), Aug. 1983, pp. 205-217.

38. K. Salama and C.K. Ling, The effect of stress on the temperature dependence of ultrasonic velocity. J. Appl. Phys. 51(3), March 1980, pp. 1505-1509.

39. E.J. Chern and J.S. Heyman, Determination of internal stress from the temperature dependence of the acoustic natural velocity. Ultrasonics Symp. IEEE 1981, pp. 960-963.

40. D.R. Allen, W.H.B. Cooper, C.M. Sayers and M.G. Silk, The use of ultrasonics to measure residual stresses., in Research Techniques in Non-Destructive Testing (Ed. R.S. Sharpe) Academic Press 1982, pp. 151-209.

41. P. Mahadevan, Effect of frequency on texture-induced ultrasonic wave birefringence in metals. Nature 211(5049) Aug. 6, 1966, pp. 621-622.

42. W.N. Reynolds, Preferred orientation in polycrystalline materials. J. Phys. D: App. Phys. 3, 1970, pp. 1798-1802.

43. K.W. Andrews, Elastic moduli of polycrystalline cubic metals. J. Phys. D; App. Phys. 11, 1978, pp. 2527-2534.

44. K. Salama and J.J. Wang, The use of the temperature dependence of ultrasonic velocity to measure applied and residual stresses., in New Procedures in Non-Destructive Testing (Ed. P. Holler) Springer-Verlag: Berlin 1983, Ch. 7.2, pp. 539-549.

45. G.S. Kino, D.M. Barrett, N. Grayeli, G. Herrmann, J.B. Hunter, D.B. Ilic, G.C. Johnson, R.B. King, M.P. Scott, J.C. Shyne and C.R. Steele, Acoustic measurements of stress fields and microstructure. Journ. Nondestructive Eval. 1(1), 1980, pp. 67-77.

46. G.C. Johnson, On the applicability of acoustoelasticity for residual stress determination. J. App. Mech. 48, 1981, pp. 791-795.

47. D.R. Allen and W.H.B. Cooper, The measurement of ultrasonic phase delay for residual stress determination. AERE-R10629, October 1982.

48. D.R. Allen, Accurate ultrasonic time delay measurement with EMAT's for residual stress determination. AERE-R10627, October 1982.

49. R.B. King and C.M. Fortunko, Evaluation of residual states of stress and material texture using ultrasonic velocity measurements with electromagnetic acoustic transducers. Ultrasonics Symp. IEEE 1982, pp. 885-888.

50. E.P. Papadakis, Ultrasonic phase velocity by the pulse-echo-overlap method incorporating diffraction phase corrections. Journ. Acoust. Soc. Amer. 42(5), 1967, pp. 1045-1051.

51. P.L. Edwards, Ultrasonic signal distortion and its effects on velocity measurements in dispersive constant-group-velocity media. Journ. Acoust. Soc. Amer. 73(5), May 1983, pp. 1608-1615.

52. E.P. Papadakis, Ultrasonic velocity and attenuation: measurement methods with scientific and industrial applications., in Physical Acoustics (Ed. W.P. Mason and R.N. Thurston), Academic Press: New York, 1976, Vol. XII, Ch. 5, pp. 277-374.

53. W. Sachse and Y-H. Pao, On the determination of phase and group velocities of dispersive waves in solids. J. App. Phys. 49(8), Aug. 1978, pp. 4320-4327.

54. H.J. Mc Skimin, Empirical study of the effect of diffraction on velocity of propagation of high-frequency ultrasonic waves. Journ. Acoust. Soc. Amer. 32(11), Nov. 1960, pp. 1401-1404.

55. E.P. Papadakis, Ultrasonic diffraction loss and phase change in anisotropic materials. Journ. Acoust. Soc. Amer. 40(4), 1966, pp. 863-876.

56. E.P. Papadakis, Ultrasonic diffraction loss and phase change for broad-band pulses. Journ. Acoust. Soc. Amer. 52(3), 1972, pp. 847-849.

57. D.E. MacDonald, On determining stress and strain and texture using ultrasonic velocity measurements. IEEE Trans. on Sonics and Ultrasonics SU-28(2), March 1981, pp. 75-79.

58. G.C. Johnson, Acoustoelastic theory for elastic-plastic materials. Journ. Acoust. Soc. Amer. 70(2), August 1981, pp. 591-595.

59. G.C. Johnson, the effect of plastic deformation on theacoustoelastic response of metals. Journ. Appl. Mech. 50, Sept. 1983, pp. 689-691.

60. R.B. King, G. Herrmann and G.S. Kino, Use of stress measurements with ultrasonics for nondestructive evaluation of the J integral. Eng. Frac. Mech. 15(1-2), 1981, pp. 77-86.

61. G.S. Kino, D. Husson and S.D. Bennett, measurement of stress, in New Procedures in Nondestructive Testing (Ed. P. Holler), Springer-Verlag: Berlin, 1983, Ch. 7.1, pp. 521-537.

62. G.S. Kino, J.B. Hunter, G.C. Johnson, A.R. Selfridge, D.M. Bennett, G. Herrmann and C.R. Steele, Acoustoelastic imaging of stress fields. J. Appl. Phys. 50(4), April 1979, pp. 2607-2613.

63. D.B. Ilic, G.S. Kino and A.R. Selfridge, Computer-controlled system for measuring two-dimensional acoustic velocity fields. R.S.I. 50(12), Dec. 1979, pp. 1527-1531.

64. S.D. Bennett, D. Husson and G.S. Kino, Measurement of three-dimensional stress variation. Ultrasonics Symp. IEEE 1981, pp. 964-968.

65. G. Begin, Note on ultrasonic tomography. Journ. Nondest. Eval. 2(2), 1981, pp. 147-149.

66. B.P. Hildebrand and D.E. Nufford, Mapping residual stress field by ultrasonic tomography. Proc. ARPA/AFML Review of Progress in quantitative NDE, Thousand Oaks, Calif., May 1978.

67. J.D. Young and F.C. Lederman, Quantitative ultrasonic tomographic imaging. Proc. ARPA/AFML Review of Progress in quantitative NDE, Thousand Oaks, Calif., May 1978.

DISTRIBUTION LIST

AUSTRALIA

DEPARTMENT OF DEFENCE

Defence Central

Chief Defence Scientist)
Deputy Chief Defence Scientist)
Superintendent, Science and Program) 1
Administration) copy
Controller, External Relations,)
Projects & Analytical Studies)
Defence Science Adviser (UK) (Doc Data Sheet only)
Counsellor, Defence Science (USA) (Doc Data Sheet only)
Defence Central Library
Document Exchange Centre, DISB (18 copies)
Joint Intelligence Organisation
Librarian H Block, Victoria Barracks, Melbourne

Aeronautical Research Laboratories

Director
Library
Divisional File - Structures
Authors: S.J. Rumble
J.G. Sparrow

Materials Research Laboratories

Director/Library

Defence Research Centre

Library

Navy Office

Navy Scientific Adviser

Army Office

Scientific Adviser - Army

.../cont.

Air Force Office

Air Force Scientific Adviser
Aircraft Research and Development Unit
  Scientific Flight Group
  Library
Technical Division Library
Director General Aircraft Engineering - Air Force
Director General Operational Requirements - Air Force
HQ Operational Command (SMAINTSO)
HQ Support Command (SLENGO)

Central Studies Establishment

Information Centre

Government Aircraft Factories

Manager

UNIVERSITIES AND COLLEGES

Melbourne	Engineering Library
Monash	Hargrave Library Professor T.F. Smith, Physics
Sydney	Engineering Library
RMIT Library	

SPARES (10 copies)
TOTAL (56 copies)

Department of Defence

DOCUMENT CONTROL DATA

1. a. AR No	1. b. Establishment No	2. Document Date	3. Task No
AR-004-030	ARL-STRUC-TM-416	MAY, 1985	DST 83/006

4. Title	5. Security a. document	6. No Pages
REVIEW OF ULTRASONIC VELOCITY METHODS OF DETERMINING RESIDUAL STRESS	UNCLASSIFIED	12
	b. title: U c. abstract: U	7. No Refs: 67

8. Author(s)	9. Downgrading Instructions
S.J. RUMBLE, and J.G. SPARROW	

10. Corporate Author and Address	11. Authority (as appropriate) a.Sponsor b.Security c.Downgrading d.Approval
Aeronautical Research Laboratories P.O. Box 4331 Melbourne, Vic. 3001	

12. Secondary Distribution (of this document)

Approved for Public Release

Overseas enquirers outside stated limitations should be referred through ASDIS, Defence Information Services Branch, Department of Defence, Campbell Park, CANBERRA ACT 2601

13. a. This document may be ANNOUNCED in catalogues and awareness services available to ...

No Limitations

13. b. Citation for other purposes (ie casual announcement) may be (select) unrestricted(or) as for 13 a.

14. Descriptors	15. COSATI Group
Ultrasonic test Residual stress Reviews	14020 20010

16. Abstract

This paper summarizes the techniques used to determine residual stresses. It notes that whilst velocity methods have not been refined to the stage of practical use, they show considerable promise. The theoretical basis, and the experimental techniques of the ultrasonic methods are reviewed with emphasis on the separation of the competing effects of texture and stress on ultrasonic velocity.

This page is to be used to record information which is required by the Establishment for its own use but which will not be added to the DISTIS data base unless specifically requested.

16. Abstract (Contd)		
17. Imprint Aeronautical Research Laboratories, Melbourne		
18. Document Series and Number Structures Technical Memorandum 416	19. Cost Code 24 6930	20. Type of Report and Period Covered
21. Computer Programs Used		
22. Establishment File Ref(s)		